Tracking and Data Relay Satellite System (TDRSS) Navigation With DSN Radio Metric Data

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This study explores the use of DSN radio metric data for enhancing the orbit determination capability for TDRS. Results of a formal covariance analysis are presented which establish the nominal TDRS navigation performance and assess the performance improvement based on augmenting the nominal TDRS data strategy with radio metric data from DSN sites.

I. Introduction

In the mid 1980's NASA will support low-altitude Earth-orbiting spacecraft missions with a Tracking and Data Relay Satellite System (TDRSS). Two geosynchronous relay satellites spaced 130° apart will serve as primary communication links and sources of metric data for low Earth orbiters. A dedicated ground tracking system will be constructed for TDRS navigation. This article explores the use of DSN radio metric data for enhancing the orbit determination (OD) of the relay satellites and for serving as a backup for the proposed TDRS ground tracking system.

The study describes the current baseline plans for TDRS navigation support and evaluates the navigation performance based on augmenting the nominal TDRS metric data with DSN-generated radio metric data. In addition, the potential role of data from a proposed fourth DSN terminal is explored in relation to TDRS navigation. Justification for this terminal is based on the relay-satellite ground station viewing constraints, and the necessity to track each TDRS with two widely separated sites. The rationale for this fourth terminal for deep space missions is also briefly reviewed.

Results of a formal covariance analysis are presented which establish the nominal TDRS orbit determination capability and assess the navigation performance with data from DSN sites. Strategies using DSN range and interferometric data in conjunction with the baseline TDRS metric data are evaluated.

Study objectives are restricted to the orbit determination for the individual relay satellites. The effect of TDRS navigation errors on the ability to recover orbits of user satellites is not examined. However, studies conducted by the Goddard Space Flight Center (GSFC) (Ref. 1) have demonstrated that the relay satellite navigation error is a dominant error source for user satellite orbit determinations. A second issue which is not addressed is the compatibility between the DSN Tracking System and the TDRS.

II. Fourth Terminal Rationale

Navigation of future deep space missions is expected to rely on precise dual-station radio metric data types such as nearly simultaneous range and ΔVLBI. Data acquisition depends on the mutual visibility of the probe from two widely separated sites with the information content of the data dependent on the interstation baseline length. With the existing three-site network, dual-station tracking opportunities typically range from 2 to 5.5 hours for spacecraft at declinations between $\pm 20^{\circ}$. Hence, tracking opportunities for data generation are limited and loss of any site for a prolonged period can significantly degrade the navigation performance. For this reason an appropriately located fourth site is an attractive option for navigation support.

The Navigation Network Project (Ref. 2) studied the potential utility of a fourth DSN terminal in Hawaii to support navigation. Because of the short baselines, it was concluded that dual-station data from this site would not serve as a backup for existing sites. The project did recommend that the fourth terminal study continue with the focus on other potential sites. Based on geometric considerations, a more desirable site location would be Santiago, Chile. This site provides north-south and east-west baseline components comparable with the current DSN sites. Furthermore, GSTDN maintains a 9-meter (receive/transmit) and a 12-meter (receive only) S-band antenna at this site (Ref. 3) at this time, although they are scheduled to be decommissioned when TDRSS becomes operational.

In addition to navigation benefits, other factors must be evaluated in developing a case for a fourth terminal. The impact of this terminal on telemetry, command, operations, radio science and geodynamics must also be assessed. For example, the DSN faces a heavy loading problem during the mid 80's due to the number of probes at negative declinations and the added responsibility of supporting highly elliptic Earth orbiter missions. A fourth terminal at Santiago will provide an additional 12 hours of communication capability for negative declination probes. The following sections assess the role of this Santiago terminal for supporting TDRS navigation. A follow on study will evaluate the application of radio metric data generated at a Santiago site for highly elliptic Earth orbiter missions.

III. Baseline System for TDRS OD

The Tracking and Data Relay Satellite System (TDRSS) (Ref. 4) consists of three geosynchronous satellites and a ground terminal near White Sands, New Mexico. Two of the satellites, TDRS-East at 41°W and TDRS-West at 171°W longitude, operate as orbiting stations to provide telemetry, command and navigation support for low altitude orbiting Earth satellites. The third, TDRS-Spare at 99°W longitude, serves as an in-orbit spare for rapid deployment in the event of a satellite failure.

To provide navigation support for the user satellites, it is necessary to precisely determine the locations of the TDRS satellites. Current plans (Ref. 4) specify daily estimation of a definitive orbit for each TDRS using metric data acquired from pairs of Bilateration Ranging Transponders (BRT) located at selected ground sites. The BRT is essentially a user transponder with a 2-foot parabolic antenna that operates in a completely automated mode. The BRT continuously receives a signal from the TDRS, but transmits only when commanded from White Sands via the TDRS. Transmission time is anticipated to be for five minutes every hour. Figure 1 illustrates the observed metric data flow, which consists of a K-band uplink from White Sands to the spacecraft, an S-band downlink and uplink between TDRS and the BRT, and a K-band downlink return to White Sands. Table 1 lists the proposed ground sites for the automated BRTs supporting each TDRS, and the corresponding DSN sites (including a Santiago terminal) which can also view the spacecraft.

Metric data from at least two widely separated sites are required for TDRS OD. For the DSN, the inclusion of a Santiago site results in visibility of each TDRS by two DSN sites.

IV. TDRS Navigation With DSN Radio Metric Data

There are two motivations for analyzing the use of DSN metric data for TDRS navigation support:

(1) As a backup for the TDRS-BRT automated ground system.

(2) To determine if the navigation accuracy for TDRS can be improved by the addition of DSN radio metric data.

To assess the role of DSN data, the study has focused mainly on the performance of the TDRS-East. Loss from Ascension Island data would significantly degrade its navigation accuracy with the position error increasing from 140 meters to 39 km. Unlike TDRS-West, there is no third BRT site to support navigation, and hence the DSN Madrid terminal and the proposed Santiago terminal are the only alternatives. Since the White Sands BRT is located in the vicinity of TDRS ground terminal, it is assumed that prolonged loss of this facility is less likely.

A linearized covariance analysis was used to evaluate the TDRS navigation performance for several tracking configurations. The nominal or baseline TDRS system performance was defined based on a BRT range data acquisition strategy and dynamics and measurement error model assumptions consistent with those used in previous TDRS OD studies at GSFC (Ref. 1). For this nominal strategy, BRT range data were acquired from two sites at a sampling rate of 1 observation per minute for 5-minute passes every hour. The performance criterion for comparing data strategies was the current state position error after 24 hours of tracking. Effects of velocity errors were evaluated by comparing the predicted state after a one-day mapping.

To supplement the BRT ranging data, it was assumed the DSN would provide either conventional two-way range or Very Long Baseline Interferometric (VLBI) data. The latter would either be in the form of differenced one-way range (DOR) or a quasar relative variant (ΔDOR). Sampling rate for the DSN range data was assumed to be the same as for the BRT system, i.e., 5-minute samples hourly. For the VLBI data types, one observation every 12 hours was sampled. Table 2 summarizes the measurement system error models for the four data types. The DOR errors are equivalent to a 3-nanosecond random component and a 10-nanosecond clock offset error. For the DSN sites the effects of station location, UT1 and media errors are reduced to equivalent station location errors. Independent ΔVLBI calibration techniques are assumed to be employed to maintain the station location errors at this 1.0-meter level.

The baseline TDRS study performed by GSFC treated solar pressure, spherical harmonics, Earth gravitational constant, BRT range bias and station location errors as systematic consider error sources. Such parameters are not modeled by the filter, but their a priori uncertainty is included in the computation of the statistics of the spacecraft state estimate. Two filtering modes were used in this study. The baseline filtering model which treats the BRT range bias as a consider parameter was the initial strategy. A second strategy which attempts to estimate the BRT range bias proved more advantageous for certain data combinations. For both filtering modes, the DSN range bias and the DOR clock offset error were considered as unmodeled parameters. Tables 2 and 3 summarize the measurement and dynamics error models.

A. TDRS-East

Figure 2 displays the current state East relay satellite OD errors for the baseline BRT range data strategy (sites at White Sands and Ascension Island) and for strategies in which the data are augmented with conventional DSN range. The filter mode for Fig. 2 (as well as Figs. 3 and 4) treats BRT range bias as a consider parameter. Individual contributions of major error sources – Earth GM, BRT range bias and stations locations – are plotted along with the total OD error. The nominal BRT system performance after one day of tracking is 140 meters. Augmenting this schedule with range from either Santiago or Madrid reduces the total error to 90 and 120 meters respectively. Including range from both DSN sites results in a 70-meter OD error. However, for this configuration the OD error is virtually insensitive to the presence of BRT range data. Effectively, this reflects more accurate DSN ranging data and the more stringent station location calibrations.

Figure 3 explores the use of DSN ranging data as a backup to the BRT system in the event of a loss of data from the Ascension Island site. Tracking from White Sands only results in a position error of 39,000 meters. The addition of ranging from either Madrid or Santiago combined with White Sands BRT data maintains the error below 240 meters. However, the performance in either case is not on a par with the baseline strategy, even with the more accurate DSN ranging. This is due to the sensitivity of the OD estimates to ground site geometry. The most desirable configuration results from simultaneously maximizing east-west and north-south separations of the tracking sites. Only the White Sands-Ascension Island or Madrid-Santiago combinations satisfy this criterion.

Figure 4 examines the effectiveness of augmenting the BRT data with either ΔDOR or DOR data. This strategy has the distinct advantage of using a receive-only antenna at the Santiago site. A data schedule of only one DOR or ΔDOR measurement every 12 hours is assumed for this phase. The results demonstrate significant improvements in position determination with ΔDOR data, and only a modest reduction with DOR data.

The availability of independent data from the DSN sites suggests the possibility of modifying the nominal filter strategy to attempt to estimate the BRT range bias parameters. Figure 5 displays the navigation performance for this revised filter model. For the baseline case, estimation of the bias degrades the performance, with the OD error increasing to 170 meters. Consequently, considering the BRT range bias is a preferred filter model for the baseline system. The bias estimation filter also fails to improve the performance for data strategies which use range from BRT and DSN sites. However, significant OD improvements are realized for options which utilize VLBI data types. In this case position errors are reduced to 20 meters with ΔDOR and 30 meters with DOR. This improvement is due to the decreased sensitivity to the unmodeled error sources such as GM which are absorbed by the estimated BRT range bias parameters.

Predicted estimates based on a one-day mapping of the state are plotted in Fig. 6 for the nominal BRT range, two site DSN range, and VLBI data strategies. The current and predicted position errors and the corresponding velocity errors for the four configurations are displayed. The addition of VLBI data significantly improves velocity estimates and limits the growth of predicted position errors. Velocity errors are reduced from 1-2 cm/sec to less than 0.25 cm/sec and predicted position errors from 200-270 meters to less than 40 meters.

B. TDRS-West

The navigation performance for TDRS-West was briefly studied assuming BRT ranging data from the Orroral-White Sands sites are augmented with data from DSN sites at Goldstone and Canberra. Since the BRT and DSN baselines are nearly equivalent, the addition of DSN data does not provide additional geometric information. The principal advantage is the increased accuracy of the DSN data types. Figure 7 displays the results of this study.

The baseline BRT system determines the spacecraft position with an accuracy of 120 meters. The addition of DSN range from both sites results in a factor of 2 improvement. However, when the baseline BRT range is augmented with either ΔDOR or DOR data the errors are reduced to the 20- to 25-meter level. The latter strategy estimates the BRT range bias parameters.

V. Conclusions

The objectives of this study were to explore the use of DSN radio metric data for supporting and enhancing TDRS navigation. DSN range data from a single site results in a modest improvement in performance for the baseline strategy. However, in the event of the loss of a BRT site such data can maintain the OD error at an acceptable level. Range data from two DSN sites reduces the OD error by a factor of 2 and essentially obviates the need for the BRT data. However, the most significant improvement results when either DSN ΔDOR or DOR data augments the BRT range. Typically, current and predicted position errors are reduced by a factor of 6 to 8 or, based on a VLBI observation, every 12 hours. This configuration also yields a tenfold improvement in estimating velocities.

The capability of the DSN to support TDRS navigaion is considerably improved by the availability of a fourth DSN site at Santiago. Both the Spare and the East relay satellites can be tracked from this site. Furthermore, the favorable geometry of Madrid-Santiago baseline enables us to generate metric data which significantly enhances the TDRS-East navigation capability.

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References

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2. Navigation Network Study Phase B Study Report, 890-116, Jet Propulsion Laboratory, Pasadena, Calif., Oct. 1980 (an internal document).
3. Ground Spaceflight Tracking and Data Network User's Guide (GSTDN) Rev. 2, STDN No. 101.3, June 1980.
4. Salzberg, I. M., "TDRSS Program Review – Bilateration Tracking," presented to NASA, Dec. 1979.

Table 1. BRT and DSN candidate tracking sites

TDRS	BRT sites	DSN sites
West	Orroral, White Sands (Samoa)	Canberra (CAN), Goldstone (GLD)
East	Ascension, White Sands	Madrid (MAD), Santiago (AGO)
Spare	Samoa, White Sands	Goldstone, Santiago

Table 2. TDRS dynamic error model assumptions

Error source	Magnitude
GM	1×10^{-6} of nominal value
Solar radiation	10% of nominal
Spherical harmonics	Full difference between APL and SAO models

Table 3. Measurement error model assumptions

	BRT	DSN		
Error source	Range	Range	ΔDOR	DOR
Random error M	2.0	0.3	0.3	0.9
Bias M	10.0	2.0	–	3.0
Station location M (all components)	10.0	1.0	1.0	1.0

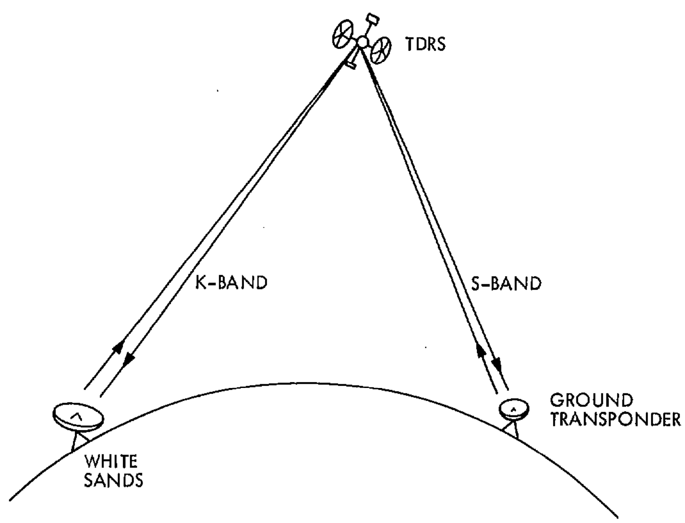

Fig. 1. Bilateration tracking of TDRS

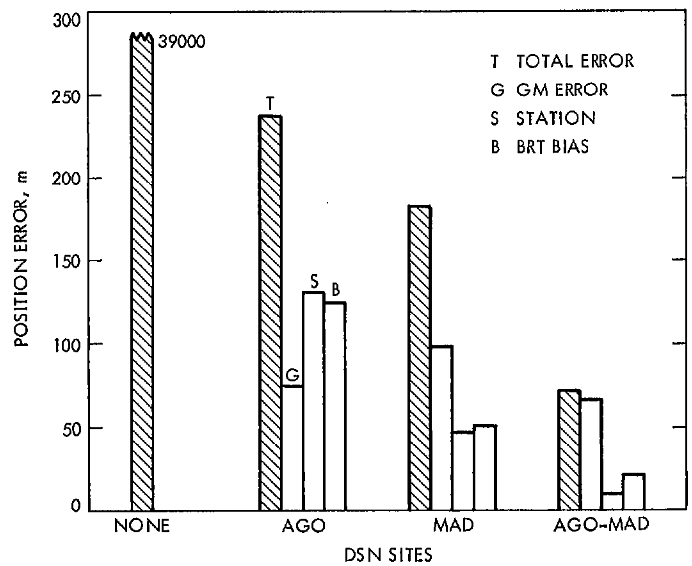

Fig. 3. White Sands BRT with DSN range

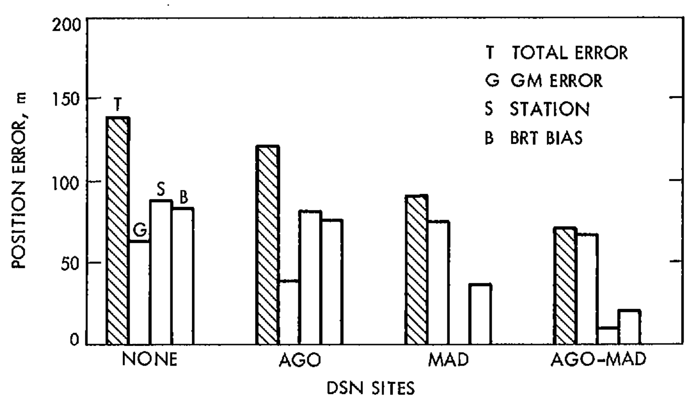

Fig. 2. TDRS-East OD with DSN and BRT range

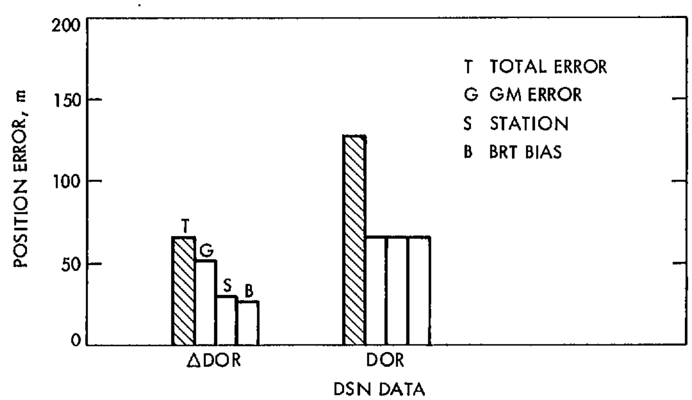

Fig. 4. TDRS OD with DSN VLBI

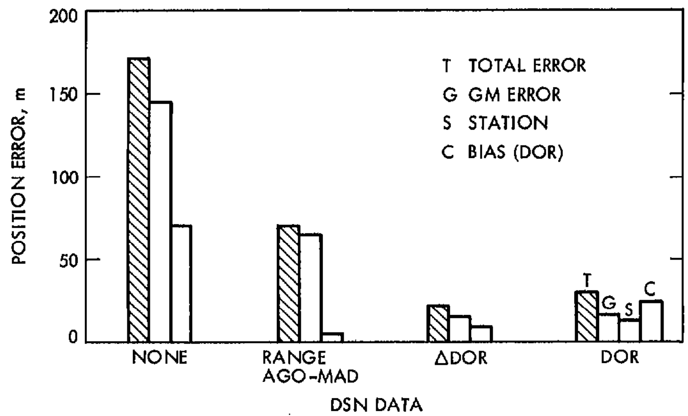

Fig. 5. TDRS OD with bias estimation filter

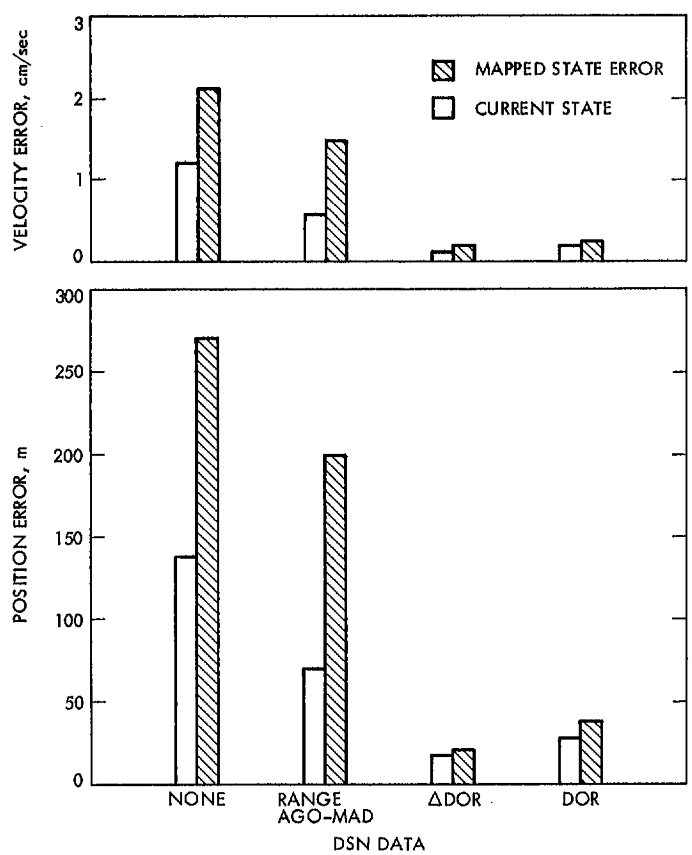

Fig. 6. TDRS-East mapped state errors

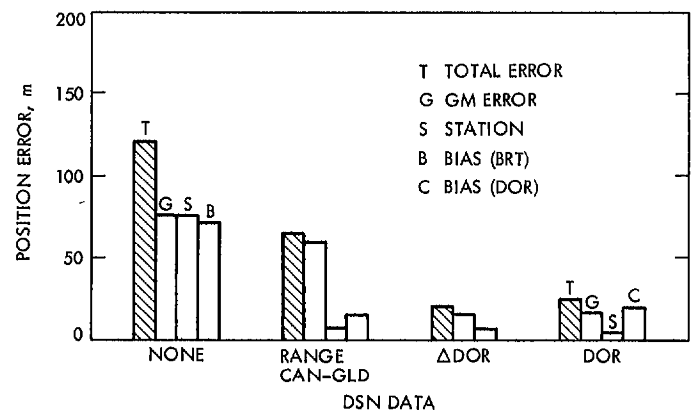

Fig. 7. TDRS-West OD performance